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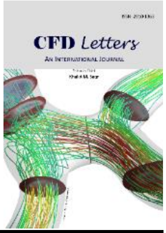

Aerodynamic Characteristics of Forward Swept Wing in Subsonic Speed

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ABSTRACT

A forward swept wing was designed to use for a supersonic aircraft. Its aerodynamic characteristics were studied through experiments and numerical simulations which excluded the subsonic speed condition. For this paper aims to explore the aerodynamic characteristics of the forward swept wing in the range of subsonic speed by using a computational fluid dynamics method. In simulation, the airfoil shape of the wing model was NACA 3412. It was varied in both swept angle and angle of attack. The airspeed was given constant at 50 m/s. The simulation results indicate that the forward swept wing model is suitable for the aerobatic aircraft because lift coefficient and the stall angle of the forward swept wing model is higher than the non-swept wing model. Moreover, the aerodynamic stall of the forward swept wing occurs at the wing root which makes the aircraft able to maintain the controllability of the aileron surface at high angle of attack. However, the aircraft with forward swept wing model tends to consume more energy as compared with non-swept wing model. Because the maximum lift to drag ratio of the forward swept wing is less than the non-swept wing. Non-swept wing model has the maximum lift to drag ratio of 8.76 at the angle of attack 2°. While the forward swept wing 35° provides the maximum lift to drag ratio of 7.47 at the angle of attack 6°.

1. Introduction

A forward swept wing was designed to improve flight characteristics of a supersonic aircraft. For this wing configuration, a wing tip was swept forward as compared with the position of the wing root. The aerodynamic characteristics of the forward swept wing were studied through the computational fluid dynamics methods which were presented in the researches [1-3]. The forward swept wing model also was compared against the backward swept wing. Setoguchi and Kanazaki [4] and Yen and Huang [5] shown the maximum lift coefficient and the stalling angle of the forward swept wing higher than the results of the backward swept wing. In 2020, Xinbing *et al.,* [6] analysed the effects of inclined angle and the swept angle. They found that the inclined angle improved the lift coefficient of the wing when flown at low angle of attack. While the swept angle increased both lift and drag coefficients. The experiments were conducted to investigate the advantages of the forward swept wing. One of the most famous aircraft with the forward swept wing is Grummen X-29. Its

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experimental results were described by Lundvall *et al.,* [7]. The flow direction of air particles moved inward from wing tip to wing root and caused the aerodynamic stall at the wing root. Thus, the aileron surfaces were not affected by unsteady flow of the aerodynamic stall. Therefore, the maneuverability and controllability of the aircraft with forward swept wing were increased and maintained even flying at high angle of attack. However, the divergence form of the forward swept wing produced the high twisting force at the wing tip. To make the forward swept wing strong enough to withstand this twisting force at high angle of attack, Rongrong *et al.,* [8] designed to construct the wing from composite material. The material thickness and orientation were optimized by using genetic algorithm (GA). The aircraft with forward swept wing usually has the problem of pitch instability because the centre of gravity is rearward the centre of pressure. Then the canard was added to increase pitch stability of the aircraft. Guoqing *et al.,* [9] and Zhang *et al.,* [10] studied the effects of canard shape (forward or backward), the relative position between the main wing and canard. They found that the aerodynamic coefficients were more affected by the relative position between canard and main wing at low angle of attack. While the geometrical shape of the canard had more effect at high angle of attack. Moreover, the improvement of aircraft lift coefficient increased 5-12.1%, when the canard position was located on the front-top position of the main wing. This improvement was reported in the researches [11-13]. In 2016, Lei *et al.,* [14] studied the aircraft with horizontal tail surface which was added instead of using canard. The study results shown the reduction of the lift/drag ratio due to the downwash effect on the tail surface. For the pitch moment of this aircraft increased as decreasing the distance between main wing and the tail wing surface. Based on the previous researches, the studies of forward swept wing were focused on the applications for the supersonic aircraft such as fighter aircraft. Consequently, there is less understanding about the aerodynamic characteristics of the forward swept wing in subsonic speed which may be used to improve the flight performance of either light aircraft or commercial aircraft.

Therefore, this article used the computational fluid dynamics method to study the aerodynamic characteristics of the forward swept wing in subsonic speed. The boundary conditions and geometry model were described. The results of aerodynamic characteristics were analysed in term of lift coefficient, drag coefficient, lift to drag ratio, pitch moment and pattern of airflow.

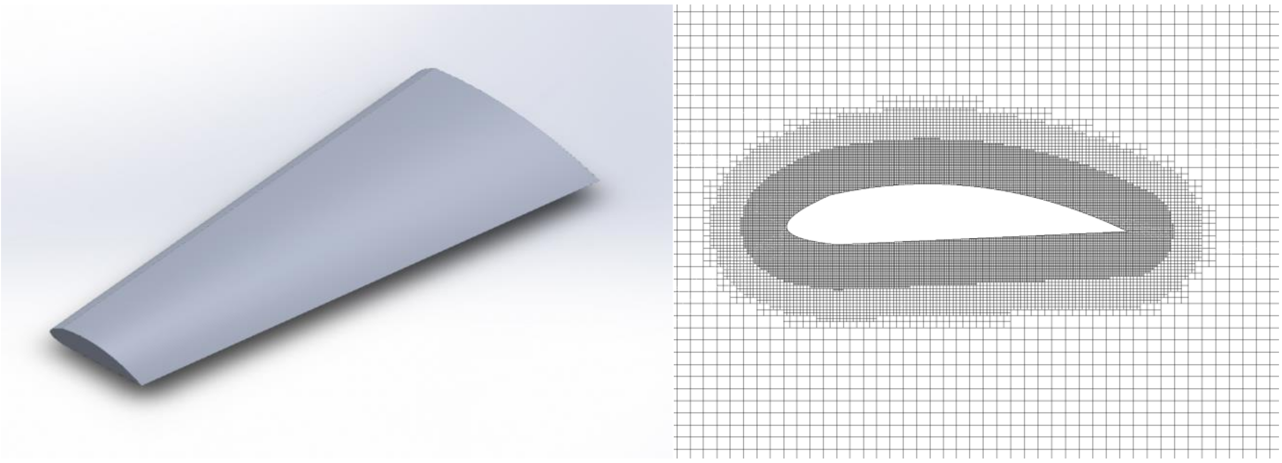
2. Numerical Simulation

An airfoil NACA 3412 was used to create the models of the forward swept wing. The length of chord line at wing root was 0.45 m. The length of wing span was 1 m. and the taper ratio from wing root to wing tip was 0.5 as shown in Figure 1(a). The swept angles of wing model were varied at 0°, 25°, 30° and 35°. While the angles of attack were varied from -2° to 18° with increment angle of 2°. The airspeed (V) was given constant at 50 m/s. The airflow was given as an ideal gas at mean sea level and Anderson., [15] was used as the reference. Therefore, the air density (ρ), air pressure (P) and temperature (T) in these case studies were 1.225 kg/m^3, 101.36 kPa and 288.2°K, respectively.

The computational fluid dynamics was performed in Solidworks software. The default size of fluid cell was given at 8.9 mm. The boundary region near to the wing surface was refined to clearly capture the airflow pattern and then the smallest size of the fluid cell was reduced to 1.1 mm as shown in Figure 1(b). The coefficient of lift (C_L) and drag (C_D) were determined by applying Eq. (1) and Eq. (2) which were taken from researches [16-18]. For the results of lift force (L), drag force (D) and wing area (A) of each case study were obtained from Solidworks software.

$$L = \frac{1}{2}\rho A C_L V^2 \quad (1)$$

$$D = \frac{1}{2}\rho A C_D V^2 \quad (2)$$



(a) (b)

Fig. 1. (a) Wing model NACA 3412 (b) Close-up view of the mesh

3. Results and Discussions

In simulation, the geometry of wing models NACA 3412 were varied in both the swept angle and the angle of attack. Then the simulation results of lift coefficient, drag coefficient, lift to drag ratio, moment coefficient, and airflow pattern were presented to describe the aerodynamic characteristics of the forward swept wing in subsonic speed condition.

3.1 Aerodynamic Coefficients

The relation between the lift coefficient and the angle of attack are presented in Figure 2. From all case studies, the results of lift coefficient tend to increase as increasing the angle of attack until obtained the maximum lift coefficient at a specific angle of attack. This angle is called the stall angle. Once the angle of attack exceeds the stall angle, the lift coefficient reduces.

When considered at the angle of attack 4°, the lift coefficient of the non-swept wing is higher than the lift coefficient of the forward swept wings. In contrast with results of lift coefficient in the range of high angle of attack, the forward swept wings are higher than the non-swept wings. The maximum lift coefficient of forward swept wing 0°, 25°, 30° and 35° are 0.79, 1.04, 1.72, 3.74 and these maximum lift coefficients are found at the following angle of attack 4°, 6°, 12° and 16°, respectively. It can be seen that the maximum lift coefficient of swept wing 35° is 4.73 times higher than the lift coefficient of the non-swept wing. This characteristic of the lift coefficient implies that the maneuverability of the aircraft with the forward swept wing is higher than non-swept wing model because it is able to produce more lift force for deep turn angle.

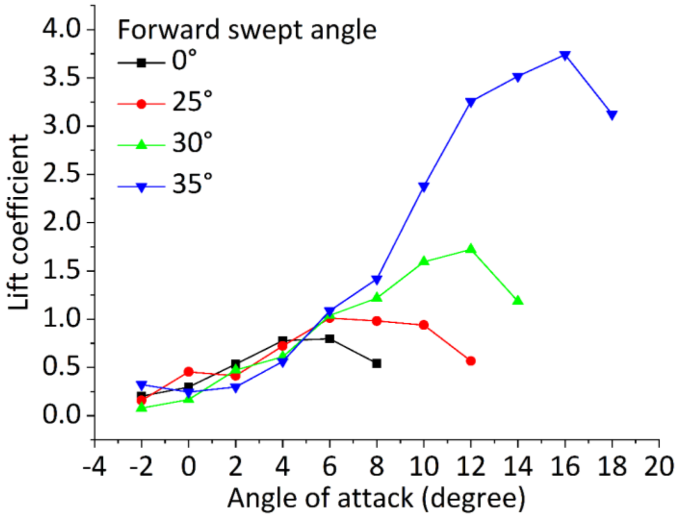


Fig. 2. The simulation result of lift coefficient

When considered the simulation results in Figure 3, the drag coefficient tends to increase as increasing the angle of attack for all case studies. At an angle of attack 4°, the drag coefficients between the forward swept wing and non-swept wing are less significant diffident. While the angle of attack between 6° to 18°, the drag coefficients of the forward swept wings are always higher than the non-swept wing. Even though the maneuverability of the forward swept wing is improved and is able to fly with high angle of attack, but it needs more power input to overcome the drag force. This statement is true when considered the results of lift coefficient and drag coefficient together as shown Figure 2 and Figure 3.

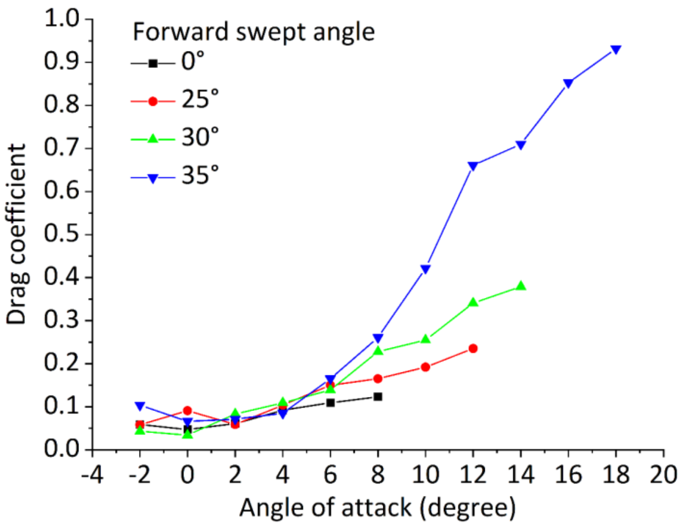


Fig. 3. The simulation result of drag coefficient

The results of lift to drag ratio are presented in Figure 4. The maximum lift to drag ratio normally is used to define the suitable angle of attack of cruise phase. Based on these studies, the maximum lift to drag ratios of both swept wing models and non-swept wing model are obtained between the angle of attack 2° to 6°. The highest lift to drag ratio is 8.76 which is obtained from the case of the non-swept wing at the angle of attack 2°. While the wing models with swept angle 25°, 30° and 35° have the maximum lift to drag ratio of 6.96, 7.47 and 6.62, respectively. Therefore, the aircraft with non-swept wing will consume less energy during cruise phase as compared with other forward swept wing models.

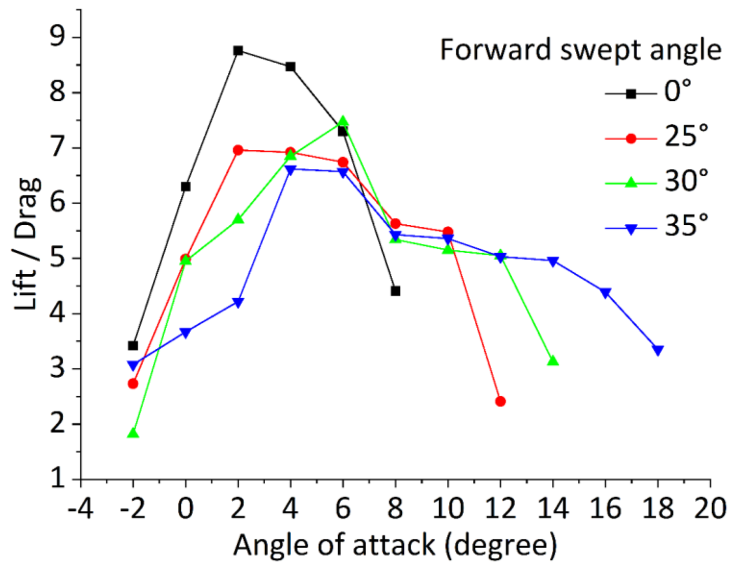


Fig. 4. The simulation result of lift to drag ratio

The results of moment coefficient are presented in Figure 5. When considered at the angle of attack between 2° to 6°, the moment coefficient of the non-swept wing is less variation and close to zero. In contrast with the forward swept wing, the moment coefficient tends to decrease as increasing the angle of attack. The moment coefficient of the forward swept wing is negative and produces the pitching down moment. This characteristic of moment coefficient implies that the longitudinal stability of the non-swept wing is more stable than the forward swept wing during the cruise phase. Therefore, the aircraft with non-swept wing can fly without compensation force from other control surface. While the forward swept wing needs other control surface to produce the compensation force for maintaining the longitudinal stability. However, the pitching down moment of the forward swept wing has a great advantage for returning the aircraft to level flight at the end of deep turn phase.

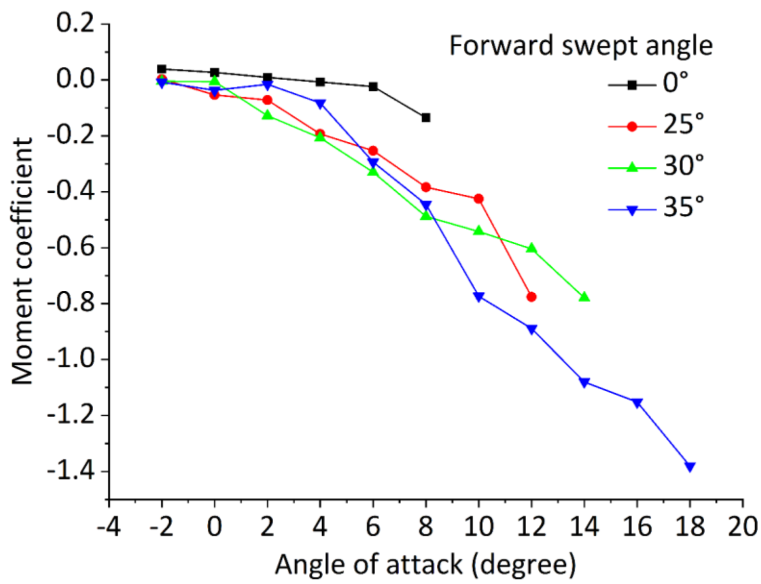


Fig. 5. The simulation result of moment coefficient

3.2 Flow Patterns

The airflow patterns of different wing models are presented in Figure 6 to Figure 7. The results of turbulence intensity are shown in each figure. The turbulence intensity indicates the ratio of fluctuation between local airspeed and inlet airspeed. The location with high turbulence intensity is higher the possibility of turbulence. The airflow patterns at the stall angle of each wing models are presented in Figure 6. For the non-swept wing at the angle of attack 4°, the airflow over the wing is streamline and the high turbulence intensity is found at the trailing edge of the outboard wing area. For the forward swept wings 25°, 30° and 35°, the locations of high turbulence intensity of these forward swept wings move to the inboard wing area. Therefore, the aerodynamic stall at high angle of attach of non-swept wing tends to occur at the wing tip location, while aerodynamic stall of the forward swept wing tends to occur at the wing root location.

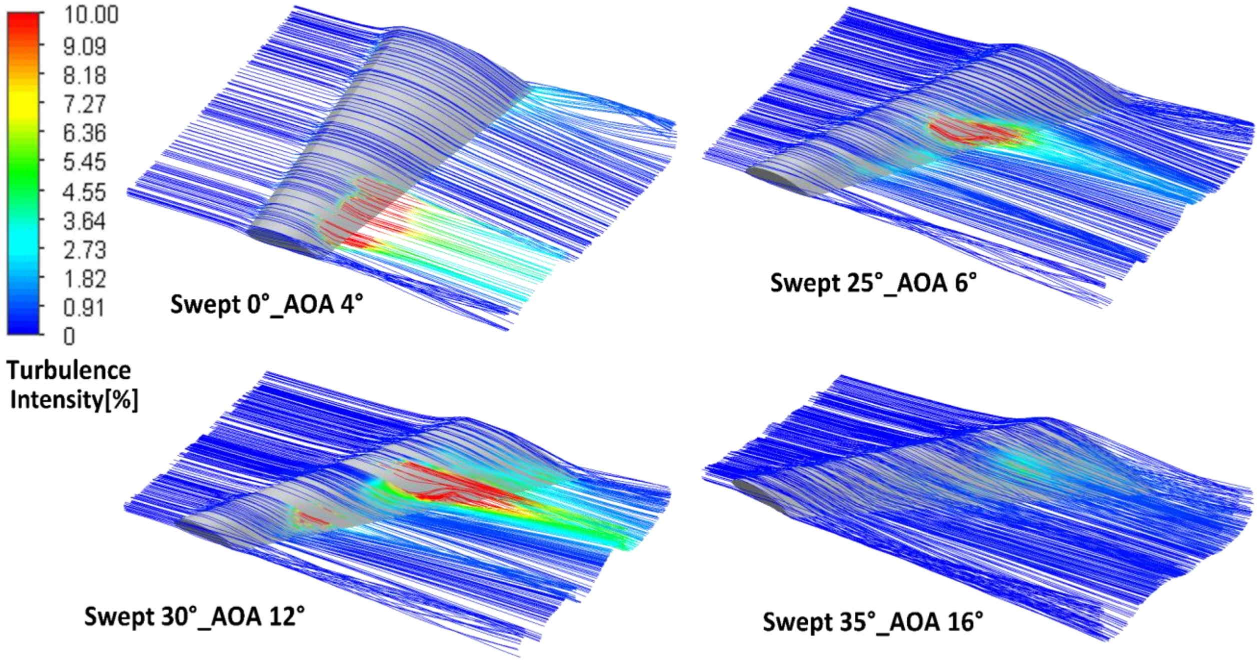


Fig. 6. Flow pattern at angle of attack with the maximum coefficient lift

At the angle of attack with the maximum lift to drag ratio, the flow patterns of different wing models are presented in Figure 7. It can be seen that the airflow patterns of all case studies are streamline. However, the high turbulence intensity is clearly seen in the outboard area of the non-swept wing as compared with other swept wing models. It means that the aerodynamic stall of the non-swept wing tends to occur earlier than the forward swept wing models.

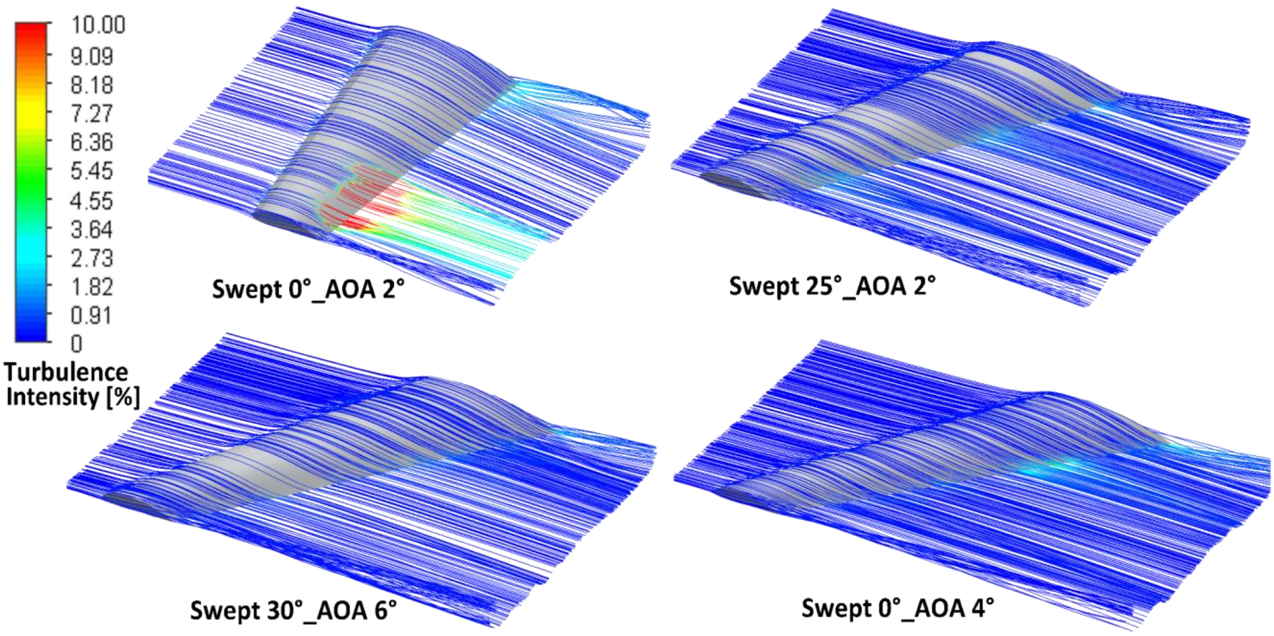


Fig. 7. Flow pattern at angle of attack with the maximum lift to drag ratio

4. Conclusions

The aerodynamic characteristics of the forward swept wing in subsonic speed were studied. The maximum lift coefficient and the stall angle increase with increasing swept angle and is higher than the non-swept wing model. The drag coefficient of both swept wing and non-swept wing models increase with increasing angle of attack and swept angle, but the difference of drag coefficients between these wing models are less significant at low angle of attack. The best lift to drag ratio of each wing model is found between the angle of attack 2°- 6° which can be classified as the suitable angle for the cruise phase. The lift to drag ratio of the non-swept wing model is higher than the forward swept wing. It means that aircraft with the non-swept wing uses less power than the forward swept wing during the cruise phase. The results of moment coefficient indicate that the aircraft with non-swept wing is more stable along the longitudinal axis during the cruise phase. While the forward swept wing models produce the pitching down moment which can be compensated with the lift force from other control surface. Forward swept wing tends to have the aerodynamic stall at the wing root. Thus unsteady flow at the wing root does not affect the airflow over the aileron surface. Therefore, the forward swept wing model is more suitable for aerobatic aircraft even though flying at subsonic speed. However, the aircraft with forward swept wing needs the higher power for both cruise phase and deep turn angle when compared to the non-swept wing.

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